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APPLICATION OF UNDERWATER LIGHT MEASUREMENTS IN NUTRIENT AND PRODUCTION STUDIES IN SHALLOW RIVERS

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APPLICATION OF UNDERWATER LIGHT MEASUREMENTS IN NUTRIENT AND PRODUCTION STUDIES IN SHALLOW RIVERS[1]

by

S.L. Wong, B. Clark and D.S. Painter

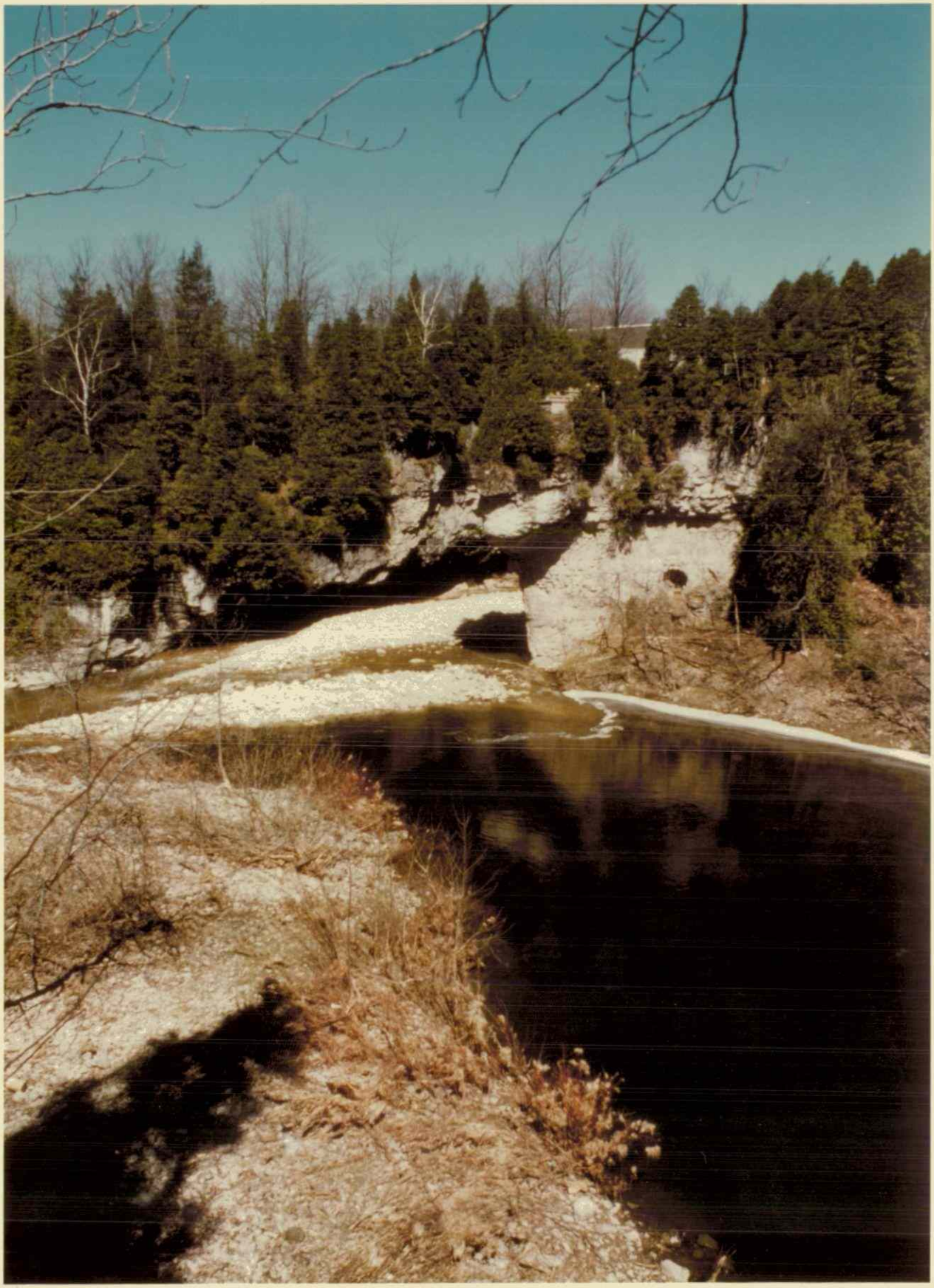
Limnology and Toxicity Section

Water Resources Branch

Ministry of the Environment

Box 213, Rexdale, Ontario

[1]Grand River Study Team Technical Report No. 2



FORWARD

This report is one of a series of technical reports prepared for the Grand River Water Resources Management Study. The project described herein was undertaken by the Grand River Study Team at the request of the Grand River Implementation Committee.

The reader is cautioned that the material contained in this report is primarily technical support information and does not necessarily represent policy or management practices. Interpretation and evaluation of the data and findings, in most cases, can not be based solely on this report but should be analyzed in light of other technical reports undertaken within the comprehensive framework of the Grand River Water Resources Management Study. Questions with respect to the contents of this report should be directed to the authors or to the Grand River Implementation Committee C/o D.N. Jeffs, Water Resources Branch, Ontario Ministry of the Environment, 1, St. Clair Avenue West, 4th Floor, Toronto, Ontario.

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ABSTRACT

Due to fluctuations in water turbidity, river depth and back-reflection from one river section to another, plant production is poorly correlated to incident solar radiation. A relationship was observed between daily relative photosynthesis and photosynthetically available radiation (PAR) at the plant depth for Cladophora, with a correlation coefficient (r) of 0.73. Therefore, the effect of low light levels can be compensated for when evaluating nutrient-growth relationships for Cladophora in the field.

Extinction coefficients with suspended solids concentration or particulate phosphorus concentration included, were determined for seven rivers. The suspended particles of each watershed had characteristic optical properties that would result in a 2.5 fold fluctuation of the 1% depth with a similar suspended solids concentration. Thus the incident solar radiation cannot be corrected by the suspended solids concentration or the particulate phosphorus concentration to approximate photosynthetically available radiation at the plant depth unless the optical properties of the suspended particles are taken into account.

This report and a following report titled "The technical aspects of measuring the plant community production in shallow streams", describe most of the methods used by the authors. This report represents the second in a series of reports presented by the Grand River Study Team and the above mentioned report will be the 8th in the same series.

INTRODUCTION

The photosynthesis of aquatic plants depends on many factors; however, it is generally accepted that the quantity of available light is the most important rate-determining factor (Ryther, 1956). The light energy received by attached plants in rivers may not relate to incident solar radiation due to extreme variation in water turbidity and, to a lesser extent, plant depth and back-reflection. Therefore, the largest uncertainty in previous production studies was the relationship between the rate of photosynthetic oxygen production and incident solar radiation (Owens et al, 1969). Plotted on log-log scale, oxygen production in River Ivel varied widely in the low light intensity range. The large variation in response of the plants to low light intensities might be explained by changing turbidity levels and/or water depth. A very small change in water turbidity under low light intensity might greatly affect the light received at the plant depth but, as light intensity increases, light saturation levels are approached or surpassed, and fluctuation in water turbidity would then have less effect. Thus, the importance of correlating photosynthetic production to the light energy received at the plant depth becomes apparent. This report discusses the relationships between photosynthesis of Cladophora glomerata, incident solar radiation, and light intensity at the plant depth, and describes the practical uses of underwater light measurements in stream productivity studies.

METHODS

The study areas chosen from six rivers in southwestern Ontario, namely the Avon, Middle Maitland, Bayfield, Nith, Conestogo, and Thames have been previously described (Wong and Clark, 1976). Cladophora glomerata was the dominant plant species appearing in the spring and remaining until the water temperature exceeded 25°C which occurred between late June and August depending on the river. Cladophora glomerata attaches itself to the substrate and grows in long filaments which are pressed against the bottom by the water current. Therefore, the depth at which the plants are growing is assummed to be the depth of the river. River sections were chosen with reasonably uniform depth so that the mean depth of the river would be an accurate plant depth for the sections studied. The mean depth of a section

was calculated by dividing its volume by the surface area. Volume was determined by multiplying the flow rate by the time of travel. Flow rates were obtained from previously derived stage-discharge relationships.

Time of travel between stations was measured with a dye tracer (Rhodamine WT) for a range of flows (Church and Kellerhals, 1970). The time of travel for any given day could then be established from its relationship to the flow. Surface area was calculated from direct physical measurements of stream length and width. Average width measurements were related to flow so that any variation in surface area as a result of changing flows could be accounted for.

Solar radiation was measured with a Weather Measure R401 Pyranometer (Weather Measure Corp., Sacramento, Calif.). The transmission of light through the water column was measured at each sampling station with an underwater quantum sensor (LI-Cor model 185, Lambda Instruments, Lincoln, Nebraska). The light sensor, corrected for cosine response, measures photosynthetically available radiation (PAR) in the 400-700 nm range. The light energy measured in microeinsteins/m^2·sec. can be converted to gram-calories assuming 1 einstein/m^2·day of visible light (400-700 nm) corresponds to about 8.4 x 10^{-3}gcal/cm^2·min. (Withrow and Withrow, 1956). Triplicate light readings were taken at each station at 10 cm below the surface and at 10 cm intervals to the bottom. The readings can be plotted on semi-log paper and the line of best fit calculated or the values can be averaged for each depth. The vertical extinction coefficient (K_e) and the 1% depth ($z_{1\%}$) can be calculated from the Lambert-Beer's Law using the average reading from two depths.

$$K_e = \frac{\ln I_1 - \ln I_2}{z_2 - z_1} \qquad (1)$$

where I_1 is the light intensity at depth z_1
and I_2 is the light intensity at depth z_2

For the special case that I_1 is the surface light intensity (100%) with a depth z_1 of 0 and I_2 is the light intensity at the unknown 1% depth $z = z_{1\%}$, then equation (1) can be rearranged to calculate the 1% depth

$$z_{1\%} = \frac{\ln 100}{K_e} = \frac{4.6}{K_e}$$

The 1% depth will be used as an expression of water turbidity (Chandler, 1942).

The light intensity was measured at three hour intervals at each sampling station. Every three hours the available light energy at the plant depth for a river section was determined as an average of the upstream and downstream measurements. Thus, plants growing within the section are assumed to receive an amount of light energy equivalent to the average of the upstream and downstream measurements. The determination of PAR at the plant depth will be discussed in detail in the results.

The gross community production was estimated by the upstream-downstream diurnal curve method described by Odum (1956) and Armstrong Gloyna and Copeland, (1968). A continuous record of diurnal oxygen fluctuation at upstream and downstream stations was obtained using E.I.L. oxygen meters (Electronic Instruments Ltd., Richmond, Surrey, England) coupled with Rustrak recorders (Gulton Industries, Manchester, New Hampshire, U.S.A.).

The method of collecting and analyzing plant samples for nutrient content has been previously described (Wong and Clark, 1976). River sections were visited every two weeks and the average phosphorus content in the plant tissue was derived from the values measured on two visits.

Suspended solids and phosphorus samples were collected using a plastic tube inserted vertically in the water. In this manner a representative water sample was obtained for the water column through which the light extinction measurements were conducted. Suspended solids samples were transported back to the lab and filtered through 0.45 μ millipore filters and dried to a constant weight at 105°C. Phosphorus samples were immediately prepared in the field for total phosphorus analysis by pipetting 50 ml of sample into acid-washed flasks. Total soluble phosphorus samples were prepared by filtering the water sample through acid-washed 0.45 μ millipore filters and pipetting 50 ml of filtered sample into acid-washed flasks. The samples were refrigerated at 4°C until digestion could be conducted in the same flask (Dillon, 1974). Particulate P could then be calculated as the difference in total P and total soluble P.

RESULTS AND DISCUSSION

Turbidity Fluctuation in Rivers

Uniform vertical mixing of suspended solids was verified as indicated by the linear plots of light intensity vs depth on semi-log graph paper. Therefore, the flow rates (0.8-8 m^3/sec) experienced will maintain uniform vertical mixing of suspended solids. Horizontal transects also revealed adequate mixing of turbidity excepting short distances from each shore. Thus, light extinction measurements from mid-stream will represent the water turbidity of the entire cross-section.

The water turbidity rarely remained constant during the day at individual stations or from one station to the next. Figure 1 illustrates the irregularity of water turbidity observed between sampling stations within a 1.5 kilometer stretch of river. Although the river sections chosen were relatively free from the effects of effluent inflows and tributaries, the fluctuations in turbidity at the downstream station was highly susceptible to factors such as the filtering mechanism of the aquatic vegetation, sedimentation of suspended particles, water depth and occasionally the scouring effect due to sudden changes in flow. Thus it is understandable that the daily light energy reaching the plant depth is not proportional to the incident solar radiation and cannot be calculated from one extinction coefficient measured at a single station.

Determination of Photosynthetically Available Radiation at the Plant depth

The mean depth, or plant depth, of the reach may vary during the course of extended production studies. The mean depth (reach volume divided by surface area) is a function of volume and therefore flow. Until the relationship between flow and mean depth has been determined, the measurement of the light energy at the mean plant depth for the reach is not possible. The following methods will allow both the determination of mean depth and the light energy associated with it after the field studies have concluded.

The light data collected from six rivers were used to verify the relationships between vertical extinction coefficient, per cent surface light and depth as described by Vollenweider (1955). The theoretical relationships expressed in the nomograph fig. 2 can be applied in our rivers since uniform vertical mixing will be maintained by the flow. For any given extinction coefficient, the depth associated with one percent of the surface light and the percent

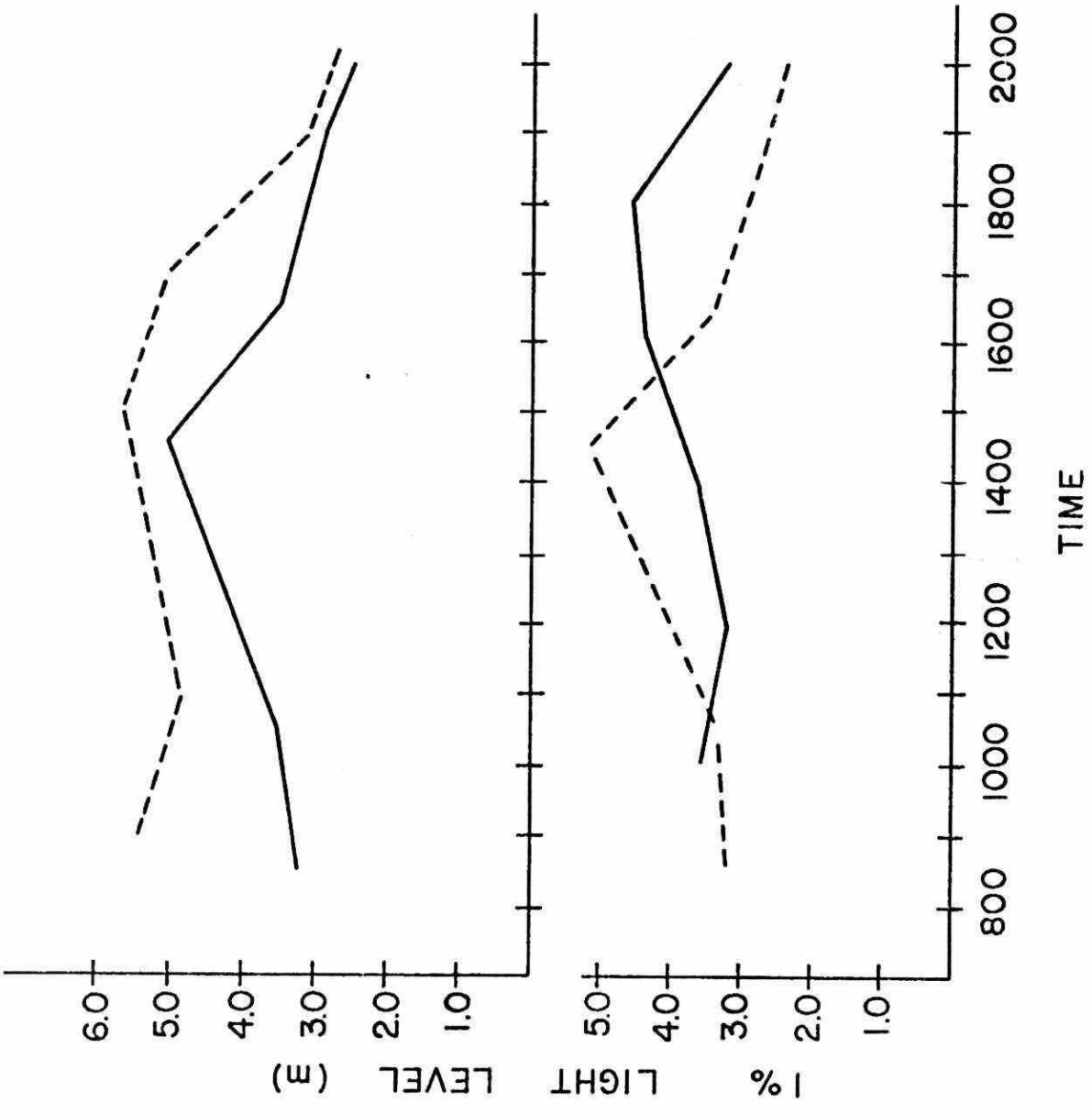


Figure 1. Daily fluctuations in turbidity expressed as the 1% light level for upstream (————) and downstream (--------) stations on the Thames River.

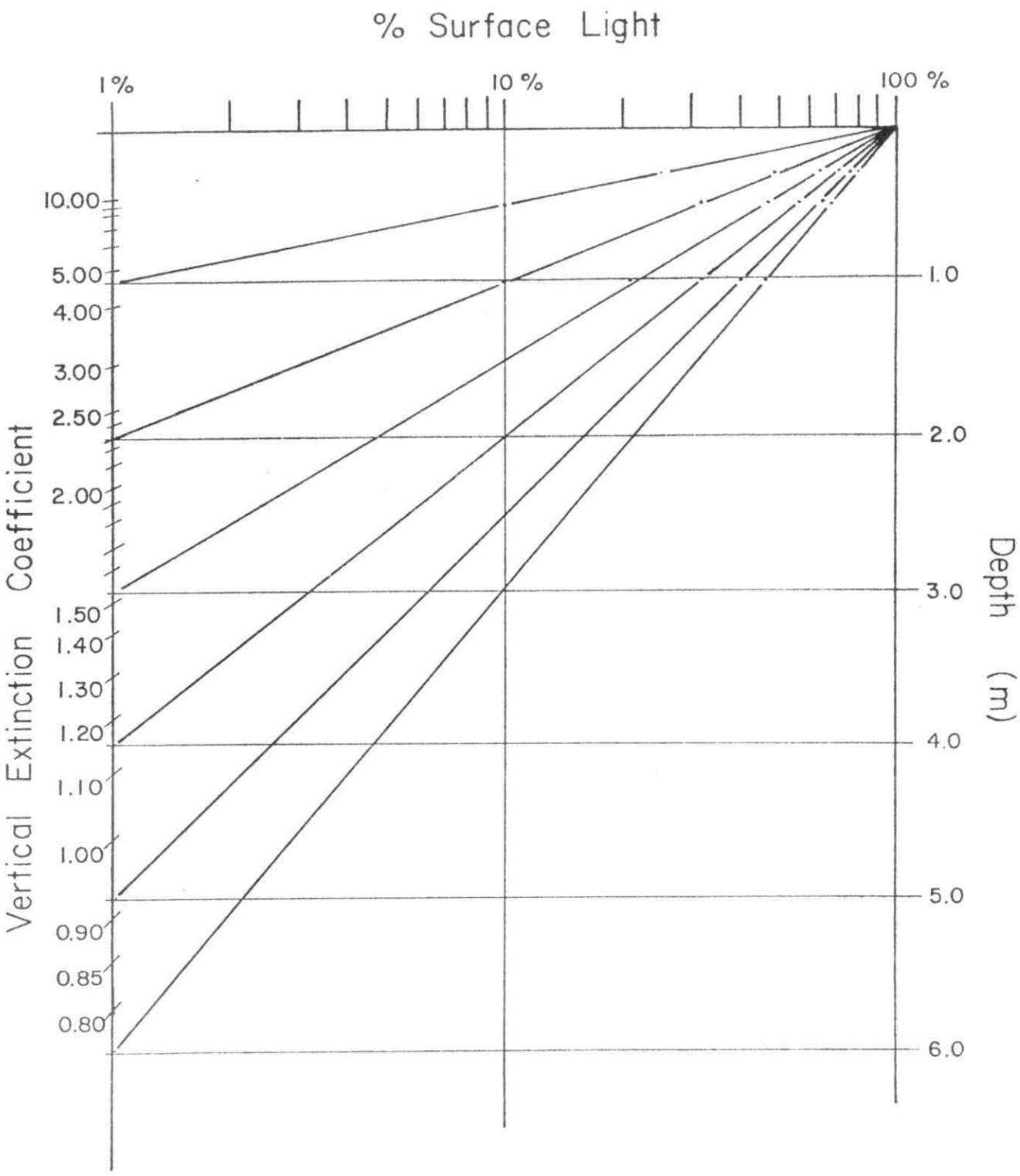


Figure 2. Nomograph showing the relationship between depth, percent surface light and the vertical extinction coefficient.

light transmission at various depths can be read from the nomograph. The percentage of surface light will be proportional to the actual quantity of light energy for different depths at any given time. Therefore, the light energy at the plant depth can be computed by determining the percentage of surface light received at that depth, and relating it to the actual quantity of light energy measured at any given depth.

Depending on the circumstances, there are various methods which may be used in working up the field data to determine the light energy at the plant depth. The light profiles at each station may include the actual measured light energy at the plant depth if the light profile was done to sufficient depths. Often, however, the light profile does not include measurements at the plant depth. In this case the nomograph may be used to calculate the actual light intensity at the plant depth. The vertical extinction coefficient is calculated (i.e 1.53) as described in the methods. The line joining the 100% surface light energy with the calculated vertical extinction coefficient is then used to calculate the percent light at the plant depth (line A). For instance if the plant depth is one meter, then using line A, the percent surface light energy at one meter is 23% (Point B). If the actual light energy at 0.5 meters was 1.0 g cal/cm^2·min. Using line A, we also know that that amount of light energy corresponds to 47% of the surface light energy (Point C). Therefore the actual amount of light energy at 1.0 meters is 23/47 x 1.0 = 0.49 gcal/cm^2·min. The actual amount of light energy at the plant depth should be calculated for each station every 2 to three hours. The upstream and downstream light energy values are averaged and plotted against time. The daily light energy for the reach at the plant depth is the graphic integration of these values, fig. 3.

Not only do varying water turbidity levels affect the transmission of light through the water column but a percentage is lost at the surface due to back reflection. Previous studies have applied a constant to account for back reflection (ie 3-5.5%, Sauberer and Eckel, 1938; 5%, Ryther, 1956; 6%, Patten, 1961; and 10%, Westlake, 1966b, Vollenweider, 1969). However, the total loss of light energy at the water's surface depends on factors such as the composition and angle of the light reaching the surface, as well as the physical nature of the water's surface. These factors make it difficult to accurately predict the percent loss due to back reflection. The present method would avoid possible errors in the use of such a constant because the actual underwater light energy is measured rather than correcting incident solar radiation measurements.

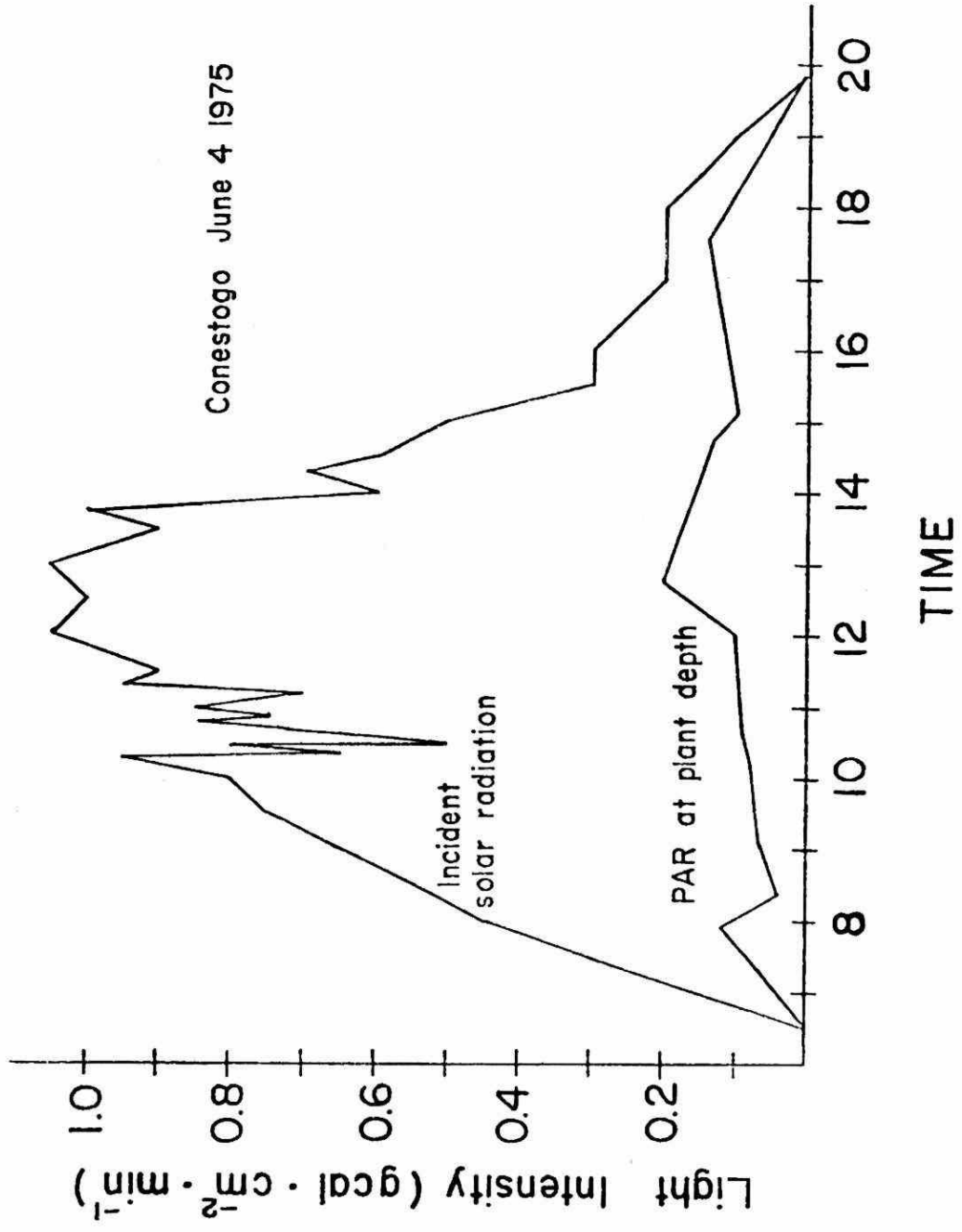


Figure 3. Incident solar radiation and Photosynthetically active radiation at the plant depth in g cal·cm^{-2}·min^{-1} plotted against time.

Rivers receiving the same solar radiation but with dissimilar mean depths, water turbidity and back reflection will exhibit different rates of gross production even though the quantitative and qualitative biomass may be identical. Estimations of available energy based on underwater light measurements, rather than on solar radiation above the water, will be independent of surface effects, water turbidity and mean depth and permit the comparison of different river systems and their corresponding production.

Relationship between PAR and Relative Growth

Daily oxygen production rates as a result of gross photosynthesis (P/day) are reported relative to the maximum photosynthesis (pmax) observed during the day. The use of these relative values (P/pmax) allows us to compare the daily growth rate of separate plant communities in different river sections without regard to the quantity of plants (Ryther, 1956). Figure 4 illustrates no relationship between daily relative photosynthesis of Cladophora and incident solar radiation. This indicates that the relative photosynthesis of Cladophora cannot be related to the available light energy measured above the water's surface. On the other hand, when daily relative photosynthesis is plotted against the PAR at the plant depth (Figure 5), a relationship with a correlation coefficient of 0.73 ($p > 0.01$) is observed. The regression line is $R = 0.59 + 4.26 \log I$, where R is in relative units and I is the light intensity at the plant depth. Although the data represents mostly the higher portion of light intensities (40-140 gcal/cm^2·day), the slope of the partial curve is similar to the complete curve described by Ryther and Yentsch (1957). Variations in water temperature may at times affect the photosynthesis of aquatic plants. Since the average maximum water temperatures recorded during the period of study was around 24-26°C, the effect of water temperature on growth has not been considered in this report. Furthermore, it is known that photosynthetic oxygen production is relatively independent of temperature when light is the limiting factor (Owens et al, 1969).

Nutrient-Growth Studies in Streams

Luxury storage of nutrients in plants (Gerloff and Krombholz, 1966; Caines, 1965) will allow aquatic plants to grow independent of the external source of available nutrients. Therefore, the tissue contents which serve as the immediate source of food, were used as an index of the availability of phosphorus for plant growth (Gerloff and Krombholz, 1966). Since growth response to nutrient supply is a long-term effect, our evaluation of the nutrient effect is based on a biweekly sampling period.

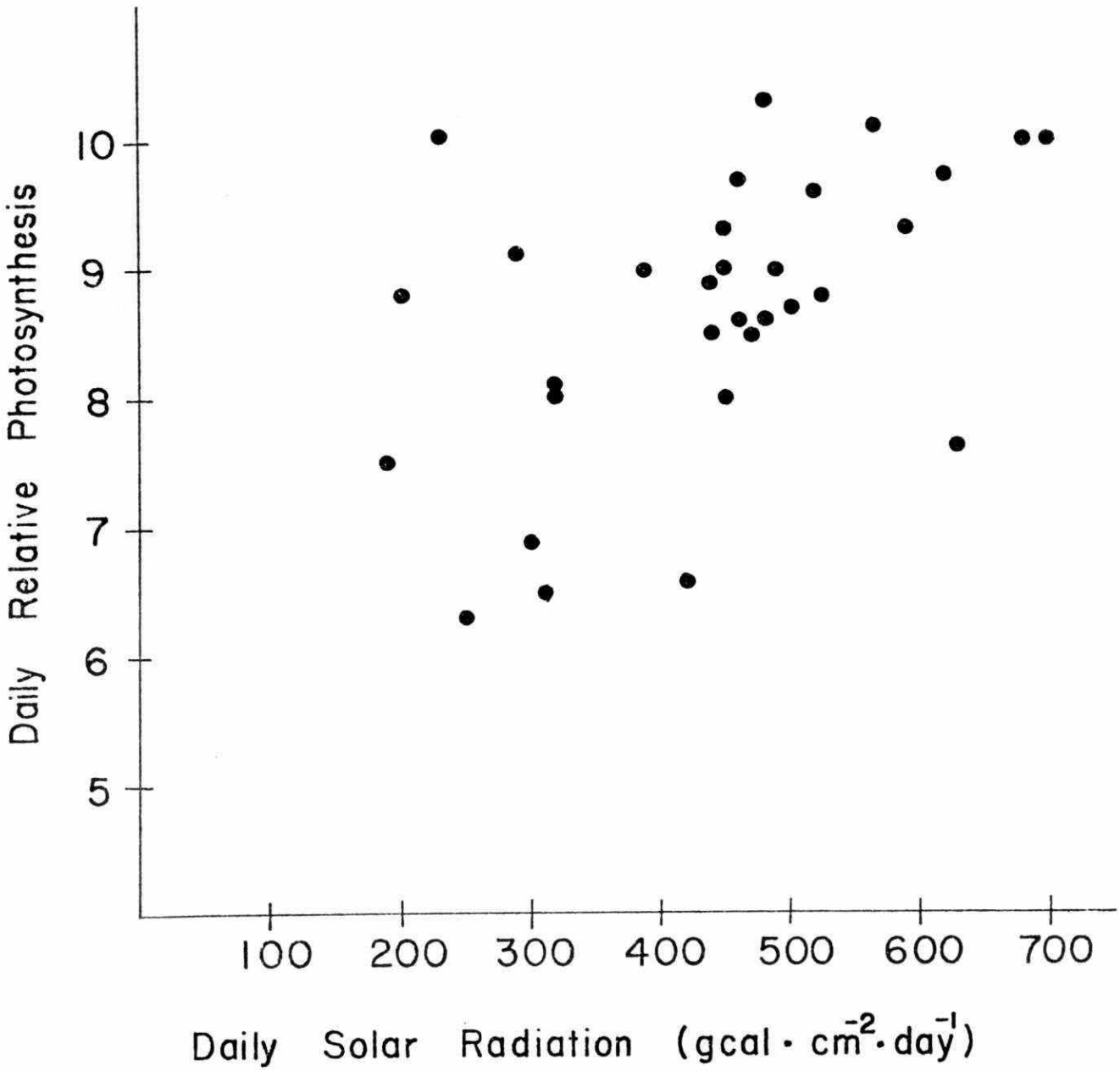


Figure 4. Relationship between Daily relative photosynthesis and Daily solar radiation.

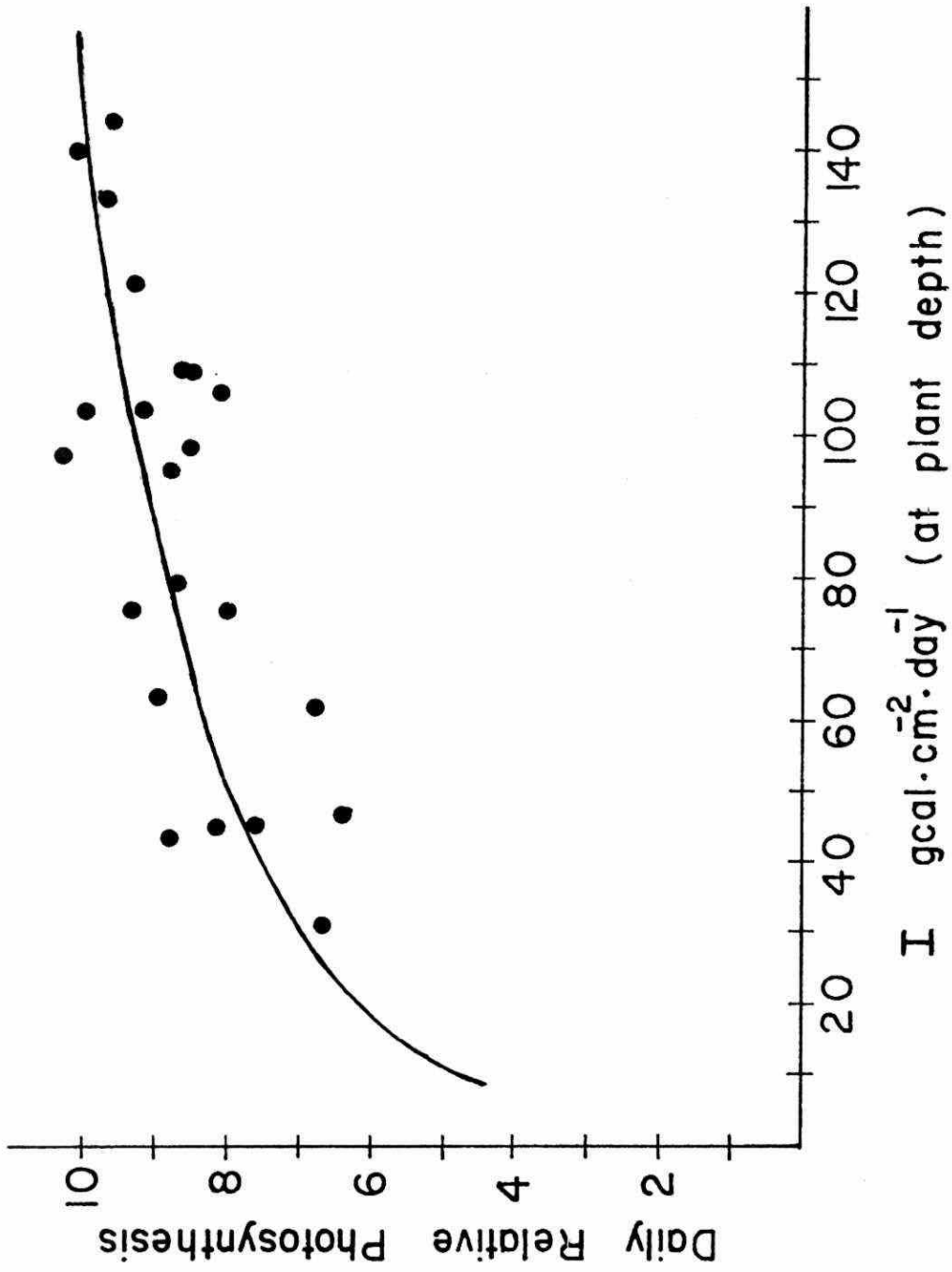


Figure 5. Relationship between daily relative photosynthesis and PAR at the plant depth for Cladophora.

Plant growth measurements have been traditionally determined from the results of plant harvesting. The quantitative measurements of any heterogeneous plant community not only require a large number of samples (Edwards and Owens, 1970; Westlake, 1974) but also fail to account for the large amount of detached, drifting Cladophora filaments (Table 1).

Table 1

N. Thames River	Transect	Drifting Cladophora Kg fresh wt. per m^2 cross-sectional area/6 hr.
May 23	T_1	8.10
	T_2	8.76
	T_3	6.06
May 25/73	T_1	2.40
	T_2	9.90
	T_3	3.24
June 20/73	T_1	1.14
	T_2	3.84
	T_3	7.92

Thus the oxygen production was measured directly for each river section and the average rate of gross production found over a two week period was used to represent the growth of the plant community (Goldman, 1972).

Since daily production is governed by nutrient supply as well as the amount of light energy available, the effect of light energy on growth cannot be disregarded and the compensation for its effect on growth response to available nutrient becomes necessary.

Compensation for the Effect of Light in Nutrient Studies

Plant growth is poorly related to available phosphorus when the effect of light intensity is not considered (Figure 6a). Application of the empirical relationship found in figure 5 will allow us to correct for the effect of light intensity and permit the observation of the nutrient effect on relative daily photosynthesis independent of the effect of light.

The daily relative photosynthesis values at measured light intensities can be corrected to a predicted daily relative photosynthesis that would occur under maximum light conditions. The maximum light intensity (PAR) observed at the plant depth for a cloudless summer day was 160 gcal/cm^2·day which corresponds to 80% transmission to the plant depth. Using this figure, the correction factor added onto the measured daily relative photosynthesis can be computed using the equation:

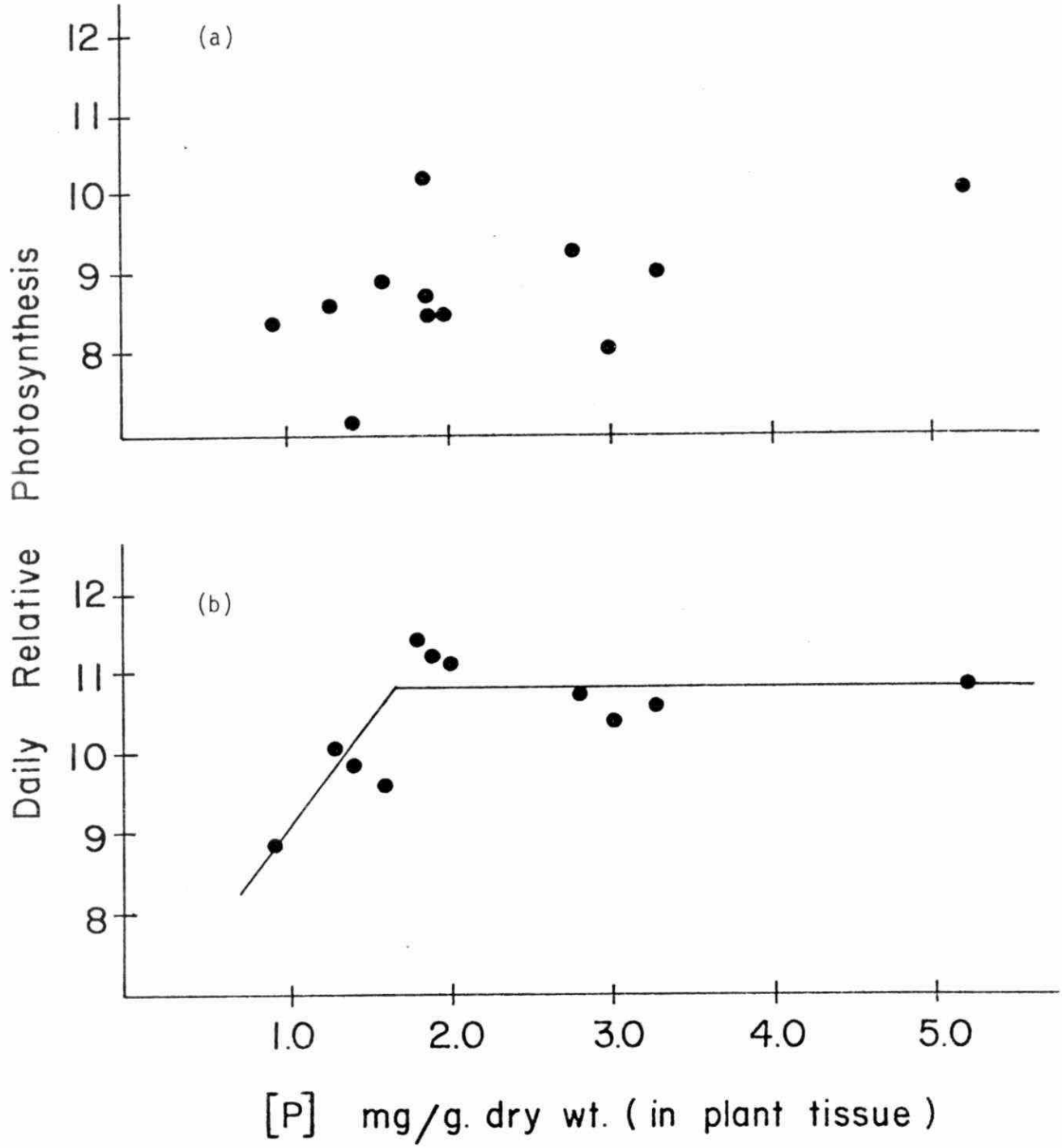


Figure 6. Relationship between Phosphorus content in the plant tissue and daily relative photosynthesis. Fig. 6a (above) before correction for light intensity. Fig. 6b (below) after correction for light intensity.

$$\Delta R = 4.26 \log \left(\frac{Imax}{I}\right)$$

$$= 4.26 \log \left(\frac{160}{I}\right)$$

Therefore, $R_{160} = R_I + \Delta R$

$$= R_I + 4.26 \log \left(\frac{160}{I}\right)$$

where R_{160} is daily relative photosynthesis at 160 gcal/cm^2·day

R_I is actual measured daily relative photosynthesis at light intensity I

and ΔR is the correction factor for R_I

Figure 6b illustrates the relationship of total P in the plant tissue and mean relative growth at a PAR level of 160 gcal/cm^2·day. After compensation for the light effect the critical phosphorus concentration was observed to be approximately 1.6 - 1.7 mg P/g. dry wt. which is in close proximity to Gerloff and Krombholz's findings under controlled laboratory conditions (1966).

From the analysis of the above graphs it is apparent that although nutrient concentration is an important factor in plant growth, it is an oversimplification to ignore the effect of variations in PAR at the plant depth on photosynthetic oxygen production.

THE EFFECT OF SUSPENDED PARTICLES ON LIGHT PENETRATION

The vertical extinction coefficient (Ke) describes the transmission of light through a one meter column of water, however, it yields no information concerning the processes that affect light transmission . The extinction coefficient can be subdivided into three separate extinction coefficients: the extinction due to water, the extinction due to the suspended particles and the extinction due to dissolved color. In lakes, the extinction due to suspended particles is largely a result of the pigments contained in the phytoplankton. However, in rivers where heavy silting occurs, the extinction due to suspended particles is a result of the optical properties of the inorganic suspended solids and to a lesser extent decaying

plant debris and sewage effluent. An evaluation of light absorption by different types of suspended matter becomes possible by introducing the quantity of suspended solids into Lambert and Beer's Law, which then appears as:

$$I_I = Io\, e^{(-k_s \cdot c \cdot z_1)}$$

$$\text{or } k_s = \frac{\ln Io - \ln I_1}{c \times (z_1 - z_o)} = \frac{4.6}{c x z_1}$$

where I_1 is the light intensity at depth z_1,

I_o is the incident solar radiation (ie 100%),

c is the concentration of suspended solids and

k_s is the extinction coefficient including light absorption effect of suspended particles (Verduin, 1954).

Theoretically, dissolved color must also be included in the extinction coefficient, however, for the rivers studied in this report, the Water Quality Data (1970-71) suggests that water color was negligible and therefore omitted from the discussion.

The frequency distribution in percent occurrence of k_s values from seven rivers indicate the modes are: Thames, 0.09; Conestogo and Nith, 0.12; Middle Maitland and Grand, 0.14; Speed, 0.21 and Upper Grand 0.24. Thus, the optical properties of the suspended solids varied in different watersheds such that the lower the k_s value the more transparent the suspended solids (Figure 7). The rivers having the lower k_s values will have more light energy reaching the plant depth assuming that the suspended solids concentrations are similar. For example, Table 2 calculates a 1% depth for each river with a suspended solid concentration of 10 mg/l.

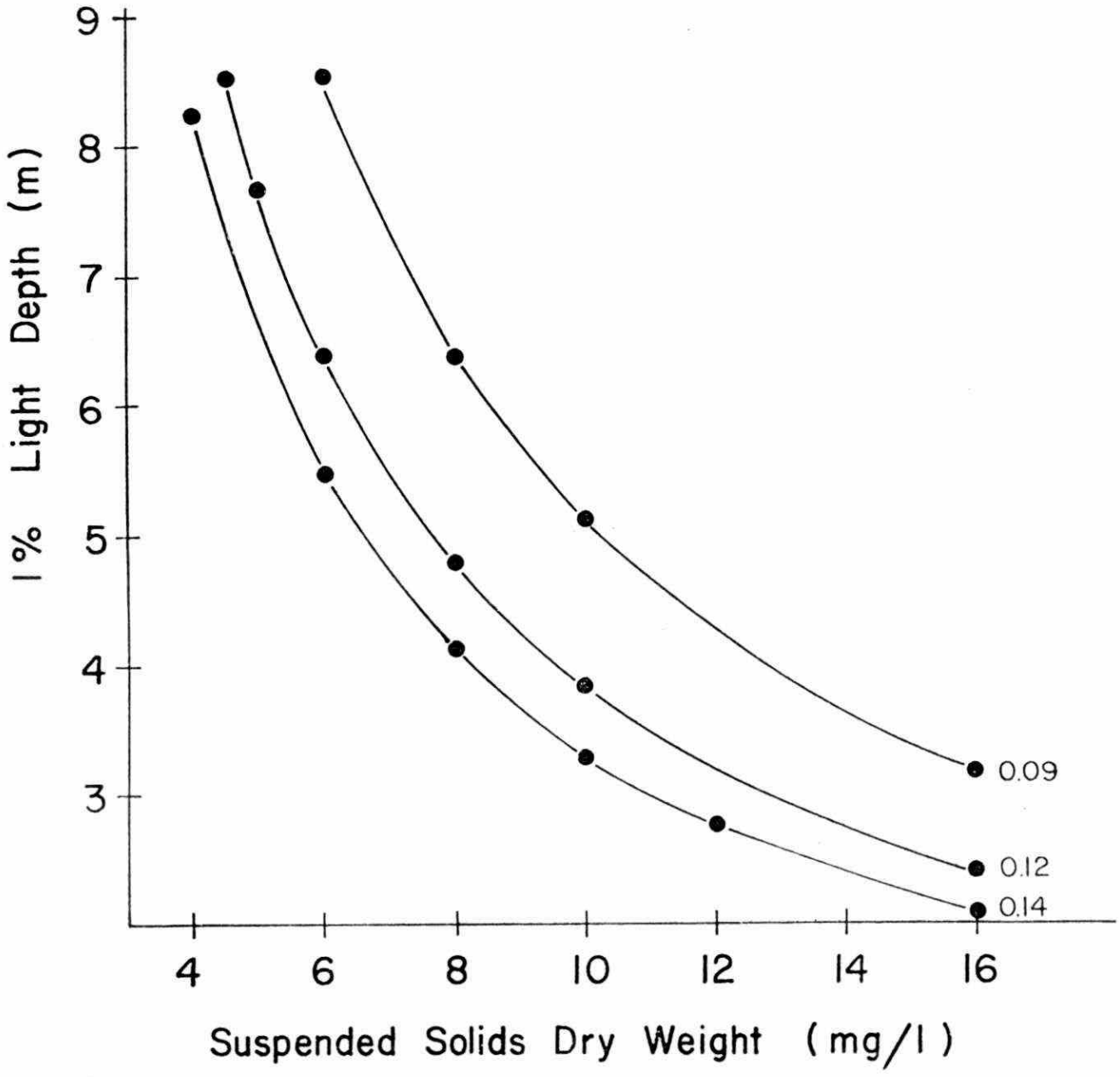


Figure 7. Relationship between the 1% light depth and the dry weight of suspended solids for different k_s values.

TABLE 2

	Thames	Conestogo	Nith	Mid-Maitland	Grand	Speed	Upper Grand
K_s	0.09	0.12	0.12	0.14	0.14	0.21	0.24
SS	10	10	10	10	10	10	10
1%d	5.11	3.83	3.83	3.29	3.29	2.19	1.92

The same concentration of suspended solids can result in fluctuations in the 1% depth as great as 2.68 fold in the seven rivers studied. Thus, the incident solar radiation cannot be modified by the suspended solids concentration to approximate the photosynthetically available radiation at the plant depth unless the optical properties of the suspended solids are taken into account.

PARTICULATE PHOSPHORUS AND LIGHT ABSORPTION

Just as Verduin (1954) recognized the potential of including the suspended solids concentration in the vertical extinction coefficient (K_s), we wish to consider the particulate phosphorus concentration in an evaluation of light absorption by different types of suspended matter (Kp). The actual concentration of suspended particles will affect the light absorbed because of the increase in particle numbers. However, the light absorption by different types of suspended matter is a result of the physical size and shape as well as the chemical content of the suspended material. Perhaps, particulate phosphorus would relate to light extinction better than suspended solids concentration because it is a measurement of the chemical nature of the suspended particles. Also to be considered is the fact that the measurement of particulate phosphorus is more accurate than suspended solids concentration and an improved relationship may result.

Therefore, Kp values were calculated for our seven river sections (Speed, 26.2; Thames, 27.7; Grand, 40.2; Upper Grand, 57.4, Middle Maitland 59.3, Nith, 60.5; and Conestogo, 70.8). The Kp value was observed to be more constant that the K_s value probably due to the increased accuracy of measurement. Statistically significant relationships existed between

particulate phosphorus concentration and 1% depth for all sections where more than 20 observations were available. The Kp value corresponds exactly to the equation of the line (Figure 8). Therefore, each river had a seasonally constant relationship between the quantity of suspended matter as measured by particulate P and light extinction. Thus, the processes that result in the type of suspended matter in the water column are constant throughout the season and the suspended matter only varies in amount but not in its chemical and optical properties. In fact, the particulate P content per mg. suspended solids had a characteristic concentration for each river section when allowances are made for the inaccuracy of suspended solids measurements.

CONCLUSION

Water turbidity fluctuates daily at individual stations as well as with progression of the water body downstream. Differences in mean depth and back reflection also affect the amount of light energy received at the plant depth. Therefore, incident solar radiation is a poor approximation of the light energy available to the plants and will not allow comparison of the effect of light on the photosynthesis of plant communities in different river sections.

The application of underwater light profiles constructed with data from individual stations not only provided an estimation of the mean water turbidity for the reach expressed as the depth associated with 1% of the surface light but also allow us to compute the actual PAR at the plant depth. This method would also eliminate the need to consider the errors resulting from various surface effects.

Daily relative photosynthesis of Cladophora has been correlated to available underwater light energy ($r=0.73$). This relationship allows us to compensate for the effect that low light intensities would have on nutrient-growth relationships by comparing daily relative photosynthesis to the available nutrients at a maximum light energy of 160 gcal/cm^2·day. This empirical relationship, while only an approximation, will serve to compensate for the variations in underwater light energy at plant depths which are encountered during daily productivity measurements.

Since little can be done to reduce the light energy for the purpose

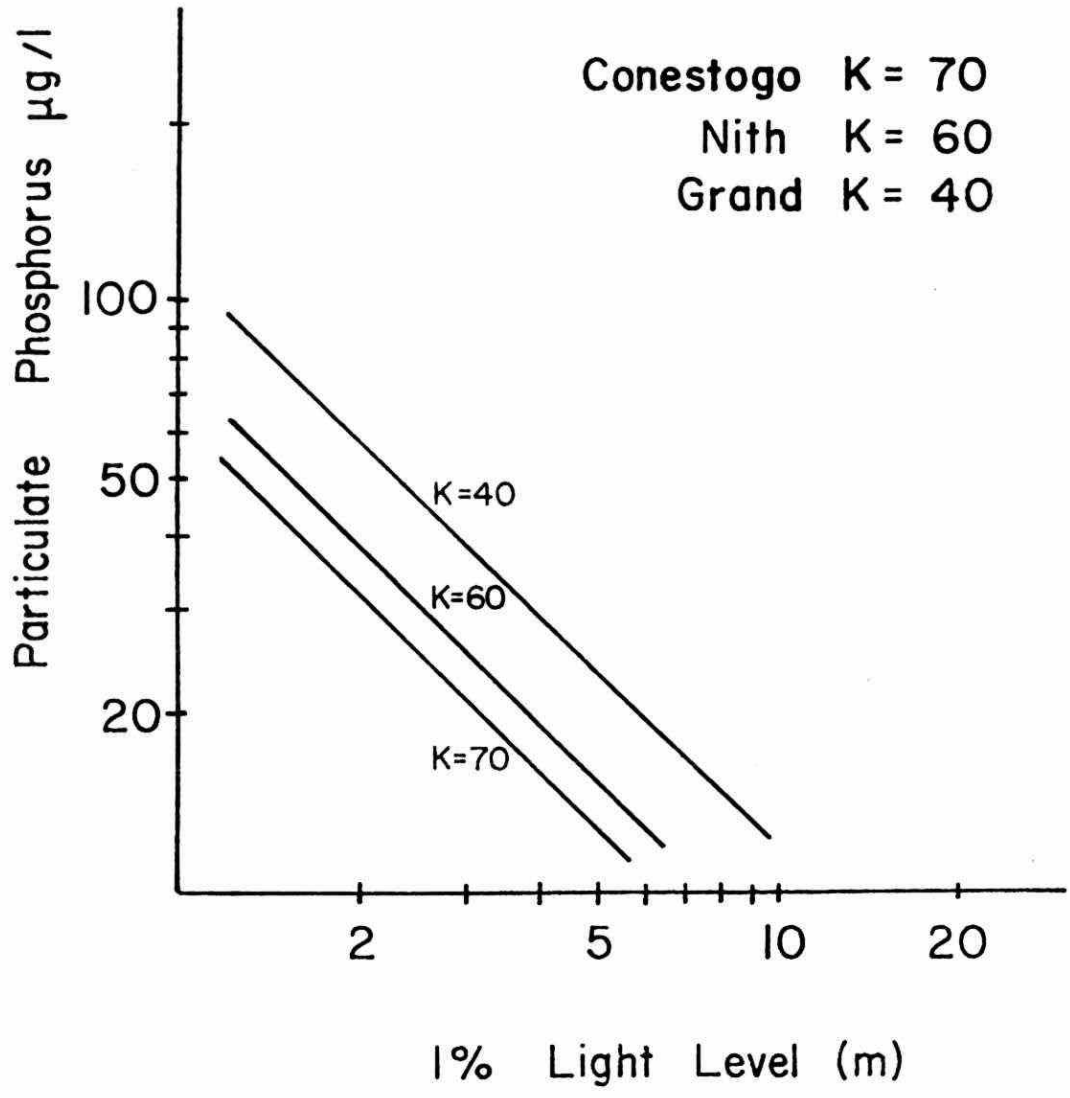


Figure 8. Relationship between the 1% depth and the particulate concentration for different k_p values.

of controlling the luxurious growth of Cladophora, nutrient suppression has always been emphasized as a possible control measure. Without compensating for the effect of light, enrichment studies in the past based on observations of nutrient-growth relationships alone have provided few reliable results. As suggested in the present study, empirical relationships between daily energy (PAR) and the daily relative growth will provide a good evaluation of the nutrient effect on growth.

The suspended particles of each watershed have characteristic optical properties that would result in a 2.5 fold fluctuation of the 1% depth with a similar suspended solids concentration. Thus the incident solar radiation cannot be modified by the quantity of suspended particles to approximate photosynthetically available radiation at the plant depth unless the optical properties of the suspended particles are taken into account.

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